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TIME-DEPENDENT PLASMA BEHAVIOR TRIGGERED BY A PULSED ELECTRON G--ETC(U)

JUL 81 E P SZUSZCZEWICZ, C S LIN

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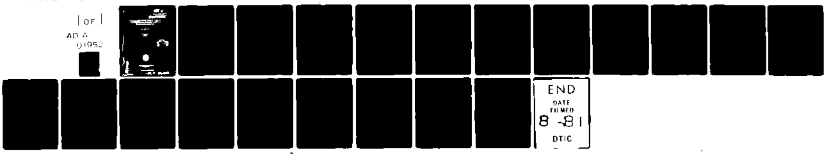

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We have conducted a number of experiments intended to simulate spaceborne applications of energetic electron guns while exploring the "in situ" diagnostics of time-dependent beam-plasma behavior under pulsed electron gun conditions. The conditions include the beam-plasma-discharge (BPD) and the BPD afterglow that exists after gun-pulse termination. With electron gun characteristics set at (I_g, V_g, T_{on}/T_{off}) = (34 ma, 1.9 keV, 80 ms/270 ms) and a superimposed magnetic field at 1.5 gauss, the results show that: (i) There is a three order-of-magnitude increase in plasma density within 5 ms of gun turn-on;

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20. ABSTRACT (Continued)

(ii) During the pulse-ON time a quasi-steady-state BPD is maintained with characteristics identical to dc-BPD conditions; (iii) Plasma losses appear to be dominated by Bohm-like diffusion processes; and finally (iv) The afterglow can be characterized by an isodensity radial profile that decays with a 36 msec time constant and cools at a $3.8(10^{3})$ K/sec rate.

3800

CONTENTS

TIME-DEPENDENT PLASMA BEHAVIOR TRIGGERED BY A PULSED ELECTRON GUN UNDER CONDITIONS OF BEAM-PLASMA-DISCHARGE

I. INTRODUCTION

An energetic electron beam, propagating through a neutral or charged-particle environment will, under various conditions, follow single particle trajectories or undergo collective effects that influence the energetic-particle orbits and render the beam-plasma system unstable to various plasma modes (Linson and Papadopoulos, 1980). From points of view focussed on single-particle behavior, there are a number of valuable spaceborne applications, among them being the mapping of geomagnetic field lines, detection of geomagnetic conjugates by the generation of artificial aurora, the study of beam spreading, atmospheric excitation and ionization processes and the measurement of magnetic field-aligned potentials. On the other hand the nonlinear processes that cannot be described by classical single-particle behavior and result in varied unstable states, represent an area of extreme interest not only to basic plasma physics but also to a large number of space-plasma phenomena that include anomalous spacecraft neutralization, enhanced ionization processes, wave-particle interactions and plasma turbulence, to name a few. While collective phenomena can significantly limit single-particle-trajectory experiments, they represent one of the most unexplored areas of controlled beam experiments in space.

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One of the areas in space-related beam-plasma interactions to receive considerable attention in recent years has been the collective plasma process called the beam-plasma-discharge (Bernstein et al., 1978; Bernstein et al., 1980; Szuszczewicz 1979; and Jost et al., 1981). The beam-plasma-discharge (BPD) describes a beam-plasma state that appears at a critical beam current I_{crit}. This critical current level yields a marked increase in ion-pair-production, a greatly enhanced 3914 Å emission, a modification of the primary beam velocity distribution and the emission of intense RF waves. The BPD has been the subject of a continuing series of space-simulation experiments (Bernstein et al., 1978; Bernstein et al., 1980, Szuszczewicz 1979; and Jost et al., 1981) that to large measure have dealt with the steady-state beam-plasma behavior in various stages ranging from pre-BPD (i.e., $I_{beam} < I_{crit}$), threshold ($I_{beam} \gtrsim I_{crit}$) and solid BPD ($I_{beam} > I_{crit}$). One such recent work (Walker et al., 1981) has determined that the density-related plasma condition for BPD threshold can be expressed as $\omega_p = (5.8 \begin{smallmatrix} +1.3 \\ -1.9 \end{smallmatrix}) \, \omega_c$, where (ω_p, ω_c) are the plasma- and electron-cyclotron frequencies, respectively. Since this result and other steady-state BPD signatures are finding what appear to be plausible theoretical descriptions (Rowland et al., 1981 and Papadopoulos, 1981), it is fair to say that the steady-state space-simulated BPD is approaching a reasonable level of accepted scientific understanding. The transfer of this understanding to spaceborne applications is accompanied by a number of conditions which to

date have not been adequately simulated or extensively studied. These conditions include the existence of a uniform and quiescent pre-beam plasma, the existence of a moving beam-plasma reference frame (as would be the case for a Shuttle-borne accelerator), an unbounded beam-length and temporal beam-plasma behavior. To close that gap and develop another perspective on space-simulated beam-plasma interactions we have conducted a number of experiments which explore the time-dependent beam-plasma behavior under pulsed electron gun conditions. The objectives included:

(i) The determination of time-dependent electron density profiles under pulsed-BPD conditions, including the BPD state itself and the BPD afterglow that exists after gun-pulse termination. The BPD afterglow is of interest in itself and conceivably bears signatures relevant to the beam-plasma wake in space (Region IV described by Anderson et al., 1979). In addition the BPD-afterglow could be used as the homogeneous pre-beam plasma for threshold studies more realistically simulating those to be investigated in space.

(ii) The test of the pulsed-plasma-probe technique (Holmes and Szuszczewicz, 1975 and Holmes and Szuszczewicz 1981) and its ability to simultaneously determine electron density, temperature, space potential and density fluctuation power spectra under pulsed electron gun conditions, and finally

(iii) The exploration and validation of previous observations of Bohm-like diffusion processes that appear to be active in a turbulent beam-plasma system (Szuszczewicz 1979).

These objectives were all accomplished and a selection of the results with experimental details are presented in the succeeding sections.

II. EXPERIMENT CONFIGURATION AND DIAGNOSTIC TECHNIQUE

The experiment was conducted in the large vacuum chamber (20 m diameter x 30 m high) facility at the NASA Johnson Space Flight Center in Houston, Texas. The chamber, with base pressures in the range 5 (10^{-7}) to 1 (10^{-6}) torr, was equipped with large current-carrying coils to generate magnetic fields up to 2.1 gauss. A steerable tungsten cathode gun was mounted near the chamber floor on a movable cart that allowed the beam to be injected upwards and parallel to the magnetic field $\bar{B}$, and terminated on a gridded 3x3 m collector suspended 20 m above the gun aperture.

The chamber was also equipped with a position-controlled cylindrical pulsed-plasma-probe P^3 (Holmes and Szuszczewicz, 1975 and 1981) that could be continuously varied in its radial separation from the beam core. All radial traversals were along the local magnetic meridian at a height of 8 m above the gun aperture. Care was taken to maintain the probe axis perpendicular to $\bar{B}$ in order to guarantee that

radial profile information was not distorted by magnetic-aspect sensitivities (Takacs and Szuszczewicz 1979). The pulsed probe itself is a specialized Langmuir probe technique which provides a high-time-resolution determination of relative electron density (1 msec resolution was utilized in this experiment) while simultaneously generating a "conventional" Langmuir probe characteristic for determination of absolute N_e, T_e and plasma potential V_∞. The technique applies a chain of voltage pulses to the probe that follows a sawtooth envelope and generates the (I_{sweep},V_{sweep}) data pairs for the conventional Langmuir probe I-V characteristic. During the interpulse period the probe is held at a fixed-baseline level, V_B, in the electron-saturation portion of the characteristic. The running measurements of I_B, during the baseline period V_B, then provide a measure of relative N_e variations (assuming $I_B = I_e^{sat} \propto N_e$).

The P^3 procedure and its application to relative N_e measurements during pulsed gun operation is illustrated with reference to Figure 1 which shows a sample of time-dependent relative density measurements (as indicated by msec baseline current samples) during three contiguous pulsed gun cycles. (Simultaneously generated sweep currents are not shown in the Figure.) The gun's current and voltage were set at (I_g,V_g) = (34 ma, 1.9 keV) and the operation cycle was at 80 msec ON and 270 ms OFF for a total 350 msec period. The results in the figure can be characterized as follows:

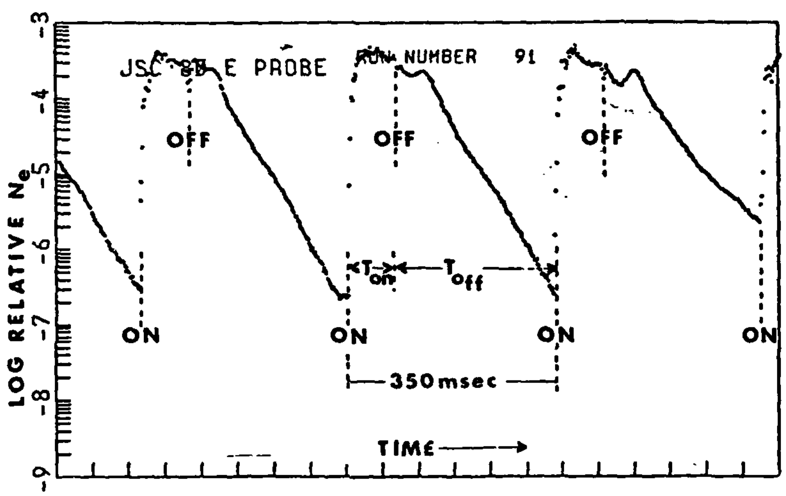

Fig. 1 — Time-dependent plasma response during three consecutive gun-pulse periods. $N_e^{max} = (1.3 \pm 0.5)\,(10^7)\ cm^{-3}$.

(a) There is a rapid enhancement in plasma density as the gun turns on (about 3 orders of magnitude increase in density in approximately 5 msec;

(b) There is a "flat" beam-plasma state during the pulse-ON time (in this case a beam-plasma discharge was achieved); and finally

(c) There is an exponential decay in plasma density once the gun pulse is terminated. Electron decay time constants were found to be 36 ± 8 msec.

Absolute electron densities and temperatures were determined by routine P^3 analysis procedures (Szuszczewicz and Holmes, 1977) summarized graphically in Figure 2, with baseline and sweep currents collected during their associated voltage intervals. The relative density variations (as indicated by the time-dependent behavior of the baseline current) were unfolded from the raw, uncorrected probe characteristic (Fig. 2A) yielding a smooth, corrected curve (Fig. 2B) to which conventional N_e analysis procedures were applied (Chen, 1965 and Szuszczewicz and Holmes 1977). With this procedure, the maximum observed electron density in Fig. 2 was $N_e(\max) = (1.3 \pm 0.5)\ (10^7)\ cm^{-3}$.

III. THE PLASMA DECAY PROCESS

As an initial step in studying the time-dependent beam-plasma process and in testing the diagnostic capability of the P^3 technique under pulsed-gun conditions, focus was placed on the BPD afterglow...it's time-dependent density decay, possible relationships to diffusion processes and associated electron cooling. For beam conditions set at

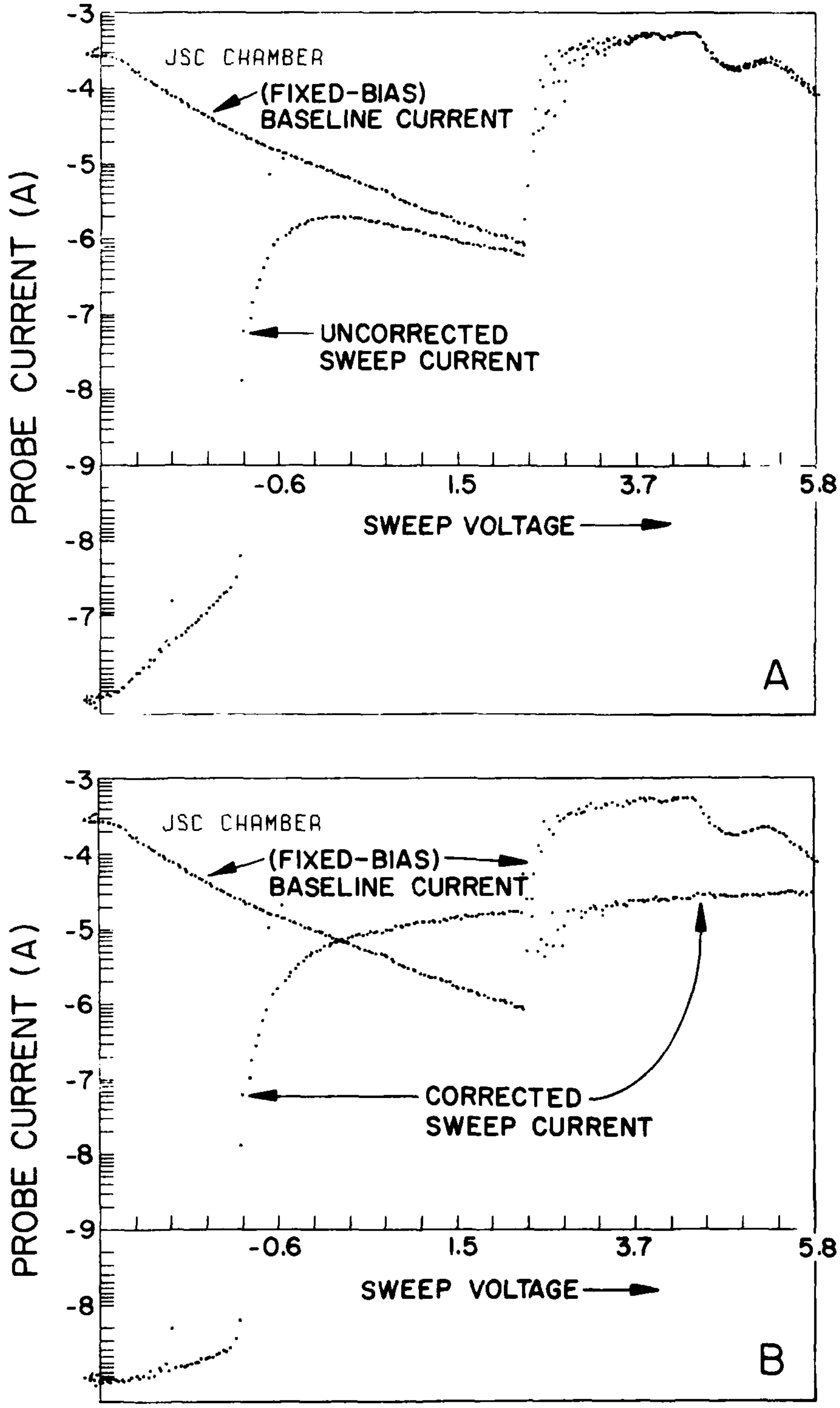

Fig. 2 — Raw P^3 data (2A) showing the effects of density variations (baseline currents) of sweep current characteristic during gun-pulse period. Fig. (2B) shows the "corrected" characteristic after density variations have been unfolded.

(I_g, V_g) = (34 ma, 1.9 keV), chamber pressure at $6.6(10^{-6})$ torr and with the superimposed field set at 1.5 gauss, a series of time-dependent beam-plasma density-profiles were generated with the gun cycle at 80 msec ON and 270 msec OFF. Because at any given position there were plasma density variations from pulse-to-pulse, a procedure of ten-pulse averaging was utilized to represent the pulsed BPD and BPD-afterglow plasmas. The relative density profiles that resulted from the averaging process is presented in Figure 3 by P^3 baseline currents I_B. The uppermost profile represents the quasi-steady-state BPD during the gun-ON period, while the four lower profiles show the radial distribution of plasma at successively later times during the BPD-afterglow, that is, during the gun-OFF period. The BPD profile (during the 10-80 msec period) is in agreement with previously published BPD conditions conducted under dc gun operation (Szuszczewicz, 1979), in that the plasma's radial dependence can be described by an exponential function, that is, $N_e = N_e^o \exp(-kr)$. In going from the BPD (10-80 msec) to the first afterglow profile (133 msec) a marked difference in radial dependence is observed. In fact, for all times in the afterglow the plasma is within ± 10% of being an isodensity profile in its radial dependence. This suggests that in the immediate after-pulse period the plasma loss is dominated by radial diffusion, a result originally suggested by the Bohm-like diffusion coefficients found in the dc-BPD profiles (Szuszczewicz

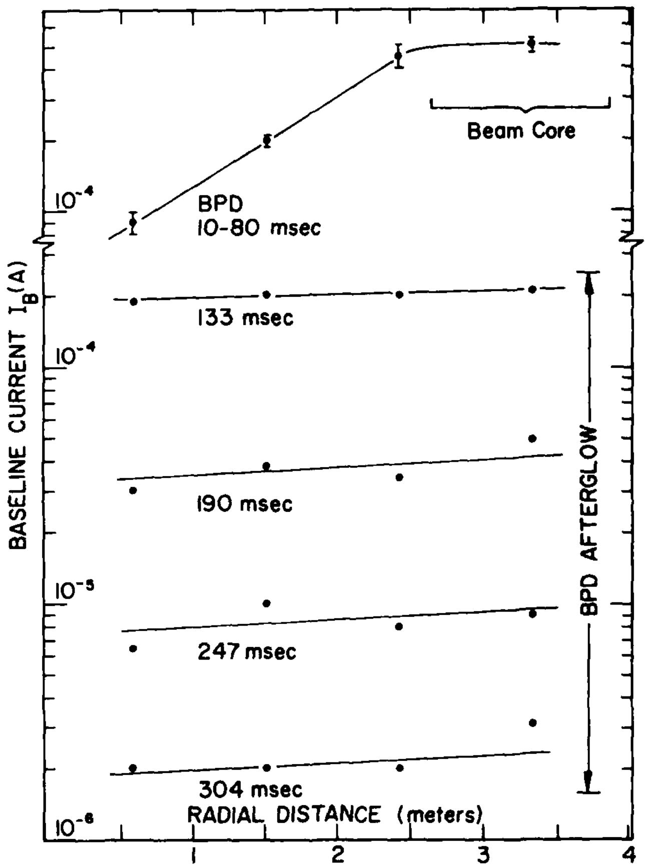

Fig. 3 — Time-dependent radial profiles of relative plasma density covering BPD (gun ON) and afterglow (gun OFF) conditions. Absolute densities can be scaled within ± 20% by $N_e I_B = 0.39$ (10^{11}) and 0.20 (10^{11}) for the BPD (10-80 msec) and afterglow profiles, respectively.

1979) where the values for D_e were found to be orders of magnitude larger (e.g., D_e(nom) = 2.2 $(10^6)cm^2/sec$) than would be expected for classical cross-field collisional diffusion in the presence of a superimposed magnetic field. If radial diffusion were not the dominant loss mechanism, the afterglow profiles would maintain qualitatively the exponential BPD (10-80 msec) profile while the plasma decayed axially. The profiles suggest just the opposite. We interpret these findings as further support for the existence of an enhanced cross-field diffusion process in the turbulent beam-plasma system characterized by the BPD.

At present one further step has been taken in studying the BPD afterglow and associated applications of the P^3 technique. This step involved determination of the electron cooling rate, with P^3 measurements of T_e presented in Figure 4 as a function of time within the gun-pulse cycle. The results can be fit with a linear function of time that points to a constant electron cooling rate equal to 3.8 (10^3) $^oK/sec$. The composite (N_e,T_e) profile information provided in Figures 3 and 4 suggest that the BPD afterglow plasma could very well prove itself to be an ideal pre-beam environment (i.e., homogeneous and Maxwellian with temperatures nearly equivalent to those found in the F-region ionosphere) for space-simulation studies of beam-plasma interactions. Indeed, the laboratory space-simulation afterglow has provided a valuable test bed for potential spaceborne applications of P^3 to beam-plasma investigations.

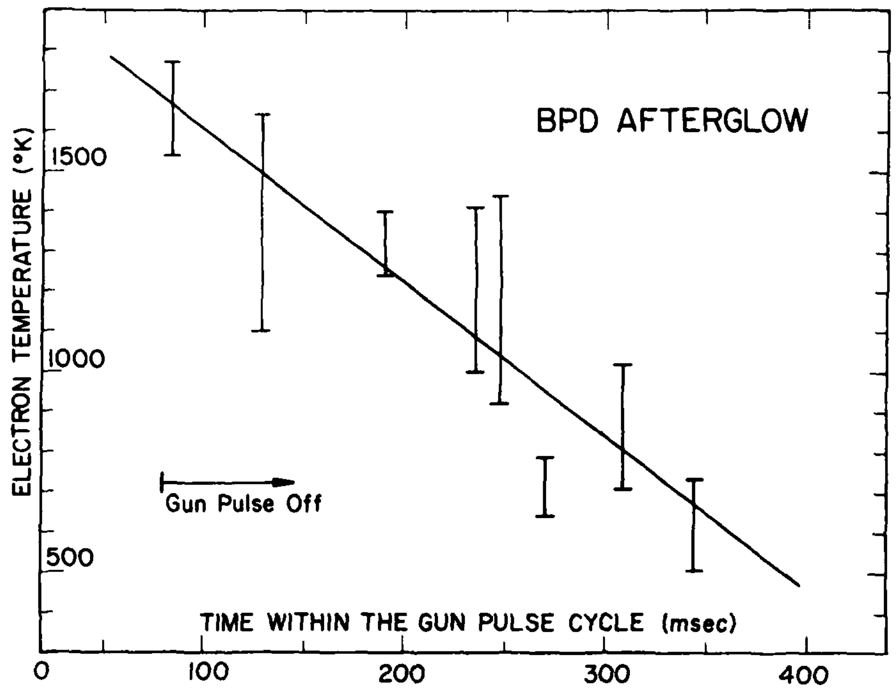

Fig. 4 — Time-dependence of electron temperature in the BPD afterglow.

IV. COMMENTS AND CONCLUSIONS

We have conducted the first "in situ" measurements of electron density profiles in a space-simulated pulsed-gun beam-plasma-discharge covering the quasi-steady-state BPD condition, its onset and its afterglow decay. While there are substantial variations with gun settings and radial-position-sampling, the observations can be characterized as follows:

(i) There is a rapid enhancement in plasma density as the gun turns on (about 3 orders of magnitude increase in approximately 5 msec for the case reported in this investigation); additional results (not reported here) show that the total enhancement and the BPD onset time are a function of gun current and energy, the superimposed magnetic field and gun ON/OFF cycle time. Details will be provided in future publications.

(ii) During the pulse-ON time a quasi-steady-state BPD can be maintained with characteristics identical with its dc counterpart.

(iii) In the period immediately following gun-pulse termination the plasma loss process is dominated by cross-field radial diffusion in keeping with an earlier suggestion that the plasma turbulence in a BPD system results in an enhanced Bohm-like diffusion process.

(iv) The afterglow plasma is within ± 10% of being an isodensity contour in its radial extent and cools linearly

with time at a 3.8 $(10^3)\,^{o}$K/sec rate with an average density decay time constant equal to 36 ± 8 msec. The BPD afterglow appears to provide an ideal pre-beam plasma environment (i.e., homogeneous and Maxwellian with $T_e^{lab} \approx T_e$(ionosphere)) for space-simulation studies of beam plasma interactions more likely to be encountered at F-region altitudes.

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